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Static and fatigue strength of RC slabs under concentrated loads near linear supports

Francisco Natário, Aurelio Muttoni

*School of Architecture, Civil and Environmental Engineering,
École Polytechnique Fédérale de Lausanne,
Station 18 CH-1015, Switzerland*

Abstract

RC slabs without shear reinforcement subjected to concentrated loads near linear supports are typical cases of deck slabs of bridges, transfer slabs or pile caps. Such elements are often designed or assessed in shear with code provisions calibrated on the basis of tests on one-way slabs or beams with rectangular cross section, even though these tests are not representative of the actual behavior of two-way slabs (non-parallel direction of shear forces and potential shear redistributions). Also the presence of prestressing ducts and slab inserts may influence the shear strength. In addition, the concentrated loads of the deck slabs are applied a number of cycles during the service life of the structure and may potentially lead to fatigue problems.

In this investigation, two experimental campaigns are presented. The first one consists of 12 static tests on 6 full-scale slabs subjected to a concentrated load with a central line support that allows evaluating the linear reaction. Parameters such as the location of the concentrated loads (3 locations) and presence of ducts (4 types) were varied. The second campaign has a similar test setup and consists of 4 static tests on 2 full-scale slabs (reference tests, failure load Q_{static}) and fatigue testing on 8 other slabs, varying the maximum applied load and the load location (2 locations). So far two slabs failed in shear ($Q_{max}=90\%$ and 80% Q_{static}) and two others due to bar fracture (fatigue in bending, $Q_{max}=70\%$ and 60% Q_{static}) that ultimately led to shear failures. All slabs that statically failed in shear showed significant shear redistributions prior to failure.

This research aims to study the observed phenomena within the framework of the Critical Shear Crack Theory (CSCT) and to provide more data to the poor existing datasets. Comparisons with the *fib*-Model Code 2010 are presented. The ultimate goals of the research are to reduce the number of existing structures that need to be strengthened and to provide consistent design methods for new structures and assessment of existing ones.

1 Introduction

RC slabs without shear reinforcement near linear supports are typical cases of bridge deck slabs, transfer slabs or pile caps. These slabs are designed/assessed under the effect of concentrated loads, which may lead to flexural, shear or punching shear failures. Studies performed in Switzerland [1], Germany [2-3] and Netherlands [4] show that for the typical European practice, shear is the most common static governing failure mode and in many cases, bridges do not comply anymore with current code provisions.

The concentrated loads that simulate heavy trucks have a repetitive nature, which may cause stiffness and strength reductions due to fatigue phenomena. In this case, the failure modes are the same as the static ones. Bending failures are due to rebar fractures and/or crushing of compressed concrete. Several studies on beams without shear reinforcement have been performed in the past [5-6].

The behavior of two-way slabs differs from one-way slabs and beams, due to the non-parallel direction of shear forces [1] and potential shear redistributions. Despite such different behavior, most available testing has concentrated only on one-way slabs and beams with rectangular cross section. As a consequence, the shear and shear-fatigue provisions of current design standards were only calibrated on the basis of such tests.

In order to study the influence of the location of the concentrated load and the presence of longitudinal prestressing ducts (typical case of cantilever bridges) or inserts, an experimental campaign of 12 static tests on 6 full-scale slabs is presented. Two parameters were varied, namely the location of the concentrated loads (3 locations) and the presence/filling of ducts (4 types).

A second ongoing experimental campaign is also presented, aiming at studying the fatigue behavior of RC slabs without shear reinforcement subjected to concentrated loads near linear supports, varying the maximum applied load and location (2 locations).

2 Test program

2.1 Test setup

Besides the actuators and the reaction frames, the test setup is identical for both test campaigns, as it is shown in fig. 1.

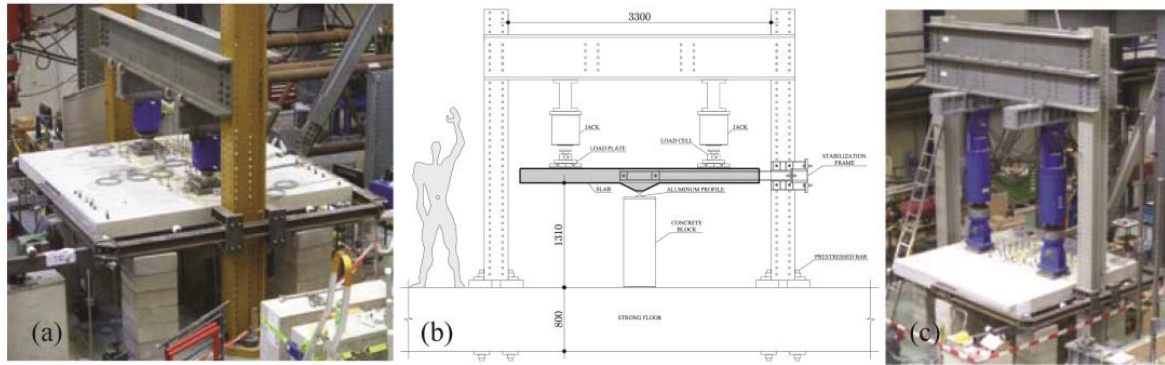


Fig. 1 Test setup: (a) static campaign; (b) elevation (dimensions in [mm]); (c) fatigue campaign

The slabs are centrally supported on an I-shaped aluminum profile equipped with vertical strain gauges on each side of the web with a constant 100 mm spacing aimed at determining the distribution of shear forces. The concentrated loads (400 mm x 400 mm) are introduced by a 10 mm thick neoprene pad, on top of which there are four 200 mm x 200 mm x 40 mm steel plates centrally loaded by a single 40 mm thick steel plate. In between there are 30 mm diameter stainless steel spheres. The slabs are partially clamped in the central region by means of two rods placed at the extremities and an external steel frame connected to one column of the reaction frame, in order to prevent horizontal displacements.

2.2 Test specimens

The geometry and reinforcement layout of the tested slabs of both experimental campaigns is showed in fig. 2.

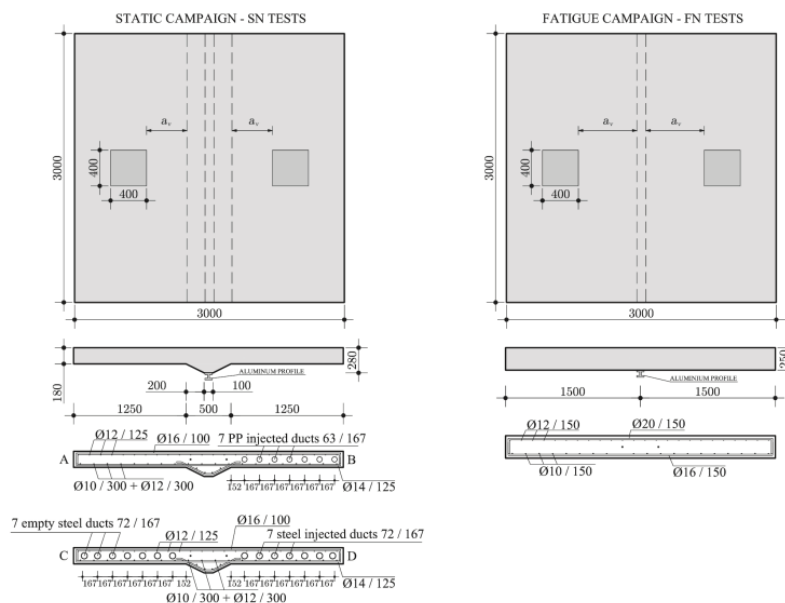


Fig. 2 Properties of tested slabs (dimensions in [mm])

2.2.1 Static campaign (SN)

In order to study the influence of load location and presence of injected ducts and inserts on the shear strength of RC slabs without shear reinforcement near linear supports a series of 12 tests on 6 full-scale slabs were performed. Three different free shear spans (distance between the edge of the support and the edge of the concentrated loads – a_v) and 4 types of ducts were tested: without ducts (reference test, A), polypropylene injected ducts (B), steel injected ducts (D) and non-injected steel ducts (C). No prestressing was applied in order to compare the different kind of slabs with the reference ones. The main reinforcement ratio was 1.32% and the concrete cover 20 mm. The concrete compressive strength measured in cylinders (f_c) was around 29 MPa and the maximum aggregate size 32 mm. Standard ribbed rebar with characteristic yielding stress of 500 MPa was used. After the first test on each slab, several holes were drilled on the side which failed in order to strengthen it, using steel profiles on top and bottom faces and prestressed bars. The second test was then carried on.

2.2.1 Fatigue campaign (FN)

This second experimental campaign is aimed at studying the influence of load location and load magnitude on the fatigue behavior of RC slabs without shear reinforcement near linear supports. Two different free shear spans and 4 different maximum applied loads will be studied, keeping constant the ratio between maximum and minimum applied load levels. For each load location 2 static tests on one full scale slab were previously performed (reference tests). The main reinforcement ratio is 1.00% and the concrete cover 30 mm. So far the concrete's compressive strength measured in cylinders was around 44 MPa and the maximum aggregate size 16 mm. Standard ribbed rebar with characteristic yielding stress of 500 MPa was used.

3 Test results

3.1 Static campaign (SN)

The shear strengths (V_{max}) of the static campaign SN are given in table 1, as well as the ratios between the free shear span and the effective flexural depth (a_v/d).

Table 1 Failure loads of the static campaign SN

Test	a_v/d	V_{max} [kN]	duct type	duct
SN1B	2	437	polypropylene	injected
SN1A	2	489	-	-
SN2B	3	341	polypropylene	injected
SN2A	3	330	-	-
SN3B	4	330	polypropylene	injected
SN3A	4	328	-	-
SN4C	2	307	steel	non-injected
SN4D	2	494	steel	injected
SN5C	3	266	steel	non-injected
SN5D	3	335	steel	injected
SN6C	4	234	steel	non-injected
SN6D	4	327	steel	injected

The load displacement diagrams of each test are given in fig. 3a, as well as a comparison of the normalized shear strengths of all tests (fig. 3b) and the evolution of the linear reaction (R_l) as a function of the total applied load for a representative test (SN3 $a_v/d = 4$, fig. 3c). For all tests, except those with non-injected steel ducts, once the peak load is achieved, a softening behavior is recorded, with an increase of the displacement with significant decrease of the applied load. The slabs with non-injected ducts present a plateau after the peak load is attained. These tests were stopped at a certain point in order to avoid excessive damage of the slabs that could prevent its strengthening. Figure 4 presents a

representative cracking pattern of a tested slab. On the top surface we can observe cracks that develop around the loading plates and parallel to the support in the central region, as well as transversal cracks on the bottom surface, under the loading plates.

The test results also show that:

- shear redistributions occur prior to failure. For initial load levels the line reaction concentrates mostly on the central region, but as the level of applied load increases, the reaction in the region close to the load increases at a slower rate and eventually decreases transferring the load to the adjacent regions.
- the effect of injected ducts on the shear strength can be almost neglected (shear strengths of tests B and D similar to reference slabs A).
- slabs with non-injected ducts (C) present a strength reduction of about 20-30% when compared with the reference tests (A). The diameter of the inserts corresponds to 45% of the effective flexural depth.
- for free shear spans greater than $3d$ the favorable effect of a better shear force distribution is compensated by the increase of bending moments, leading to smaller normalized shear strengths.

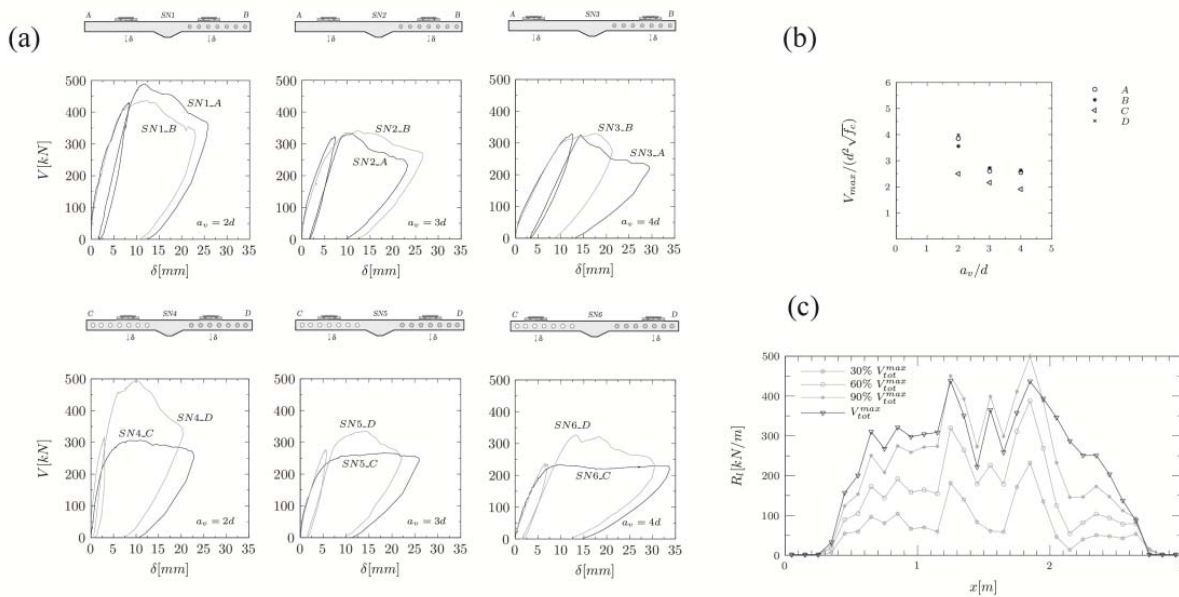


Fig. 3 Static campaign SN results: (a) load-displacement diagrams (measured at the center of the loading plates); (b) normalized shear strengths; (c) linear reaction evolution of test SN3 ($a_v/d = 4$)

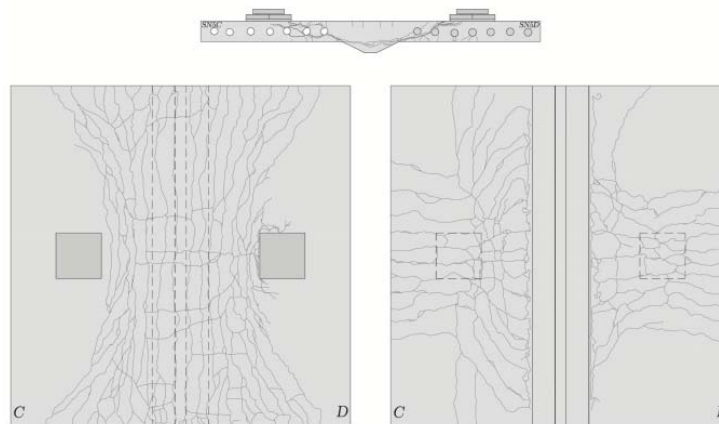


Fig. 4 Cracking patterns of a representative slab (SN5 $a_v/d = 3$)

3.2 Fatigue campaign (FN)

Two different free shear spans are used in this campaign, namely $3.24 d$ and $2.10 d$. The static reference tests failed in shear. Regarding the fatigue tests, so far only tests for $a_v = 3.24 d$ were performed. The ratio between the minimum and maximum applied loads is $R = 0.1$. The normalized maximum applied loads (divided by $f_c^{1/2}$) were 90, 80, 70 and 60% of the average normalized static shear strength. Shear fatigue failures similar to the static cases were obtained for maximum applied loads of 90% and 80% of the static strength. For the other two cases failure was due to rebar fracture of the top transversal reinforcement over the linear support, as well as the longitudinal bottom reinforcement under the loading plates. Both tests were able to carry on with the same load levels with a progressive increase of the zone with broken bars. Ultimately a shear failure has occurred after an important degradation of the slab. Figure 6 shows the Wöhler diagram (S-N diagram) of these tests.

4 Discussion of test results

Fig. 5 presents the comparison between the tests of the static campaign SN and the *fib*-ModelCode 2010 [7] approach. This analysis is based on linear elastic finite element models and the proposed geometric rule of *fib*-Model Code 2010 to calculate the shear effective width, alongside a Level II Approximation to calculate the parameter k_v . The case where no force is directly transferred to the supports (arching action) is also plotted ($\beta = 1$).

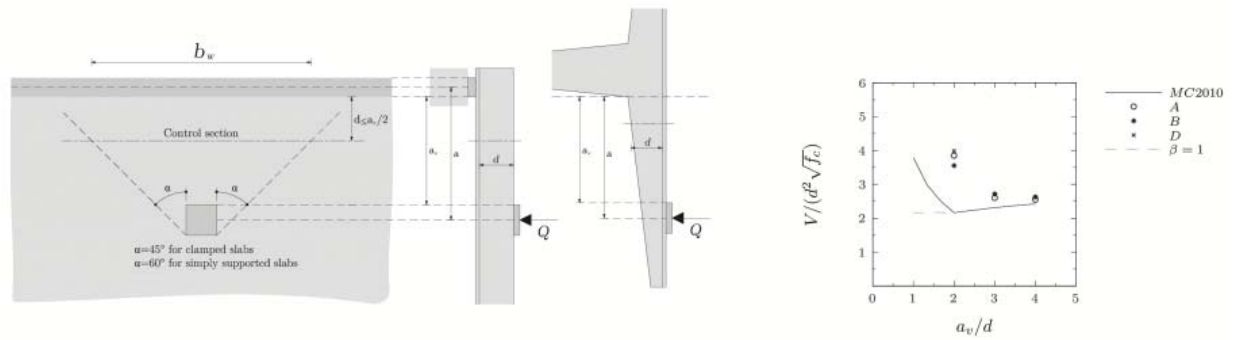


Fig. 5 Determination of effective width and comparison with static campaign (SN)

The *fib*-Model Code 2010 model is reasonably predicting the shear strength for values of a_v/d greater than 3, where arching action can hardly develop.

Concerning the shear fatigue design of reinforced concrete members without shear reinforcement, the *fib*-Model Code 2010 proposes the following relationship between the endurance N , the maximum applied force V_{max} and the static shear strength V_{ref} :

$$\log N = 10 (1 - V_{max} / V_{ref}), \quad (1)$$

which is plotted together with the tests results in the Wöhler diagram of fig. 6. For maximum applied loads between 60-90% of the static shear strength the proposed formula is about 1-2 orders of magnitude more conservative than the test results.

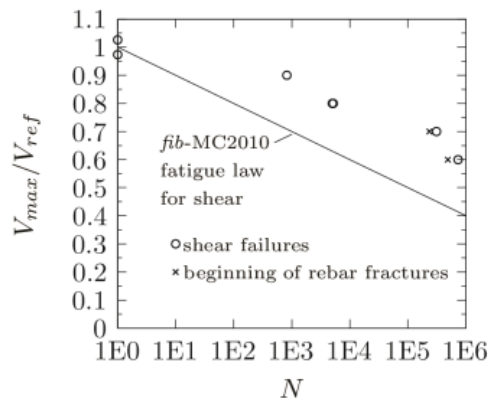


Fig. 6 Wöhler diagram of tested slabs ($a_v/d = 3.24$) and comparison with proposed formula for the shear fatigue of members without shear reinforcement of the *fib*-Model Code 2010

5 Conclusions and outlook

This paper presents two experimental campaigns on the static shear strength and fatigue behavior of reinforced concrete slabs subjected to concentrated loads near linear supports. The first campaign consisted of 12 tests on 6 full-scale slabs and the second one, so far, on 4 static tests on 2 full-scale slabs and 5 fatigue tests on 4 others. The main conclusions of these two campaigns and this paper are:

- There are different static failure modes for the studied slabs: shear, punching shear and flexure. These modes are also observed in fatigue testing.
- All static tests failed in shear, and prior to failure shear redistributions were observed.
- These redistributions show why it is inappropriate to extrapolate the empirical results of tests on beams and one-way slabs. This fact also shows the necessity of the development of adapted theoretical models experimentally validated.
- Tests with higher a_v/d relations present smaller shear strengths (tested values of 2, 3 and 4).
- No significant shear strengths differences were observed between slabs with injected ducts and reference slabs.
- Future work will consist of completing the ongoing fatigue testing campaign and the development of theoretical considerations to address these research topics in the framework of the CSCT [8].

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References

- [1] Vaz Rodrigues R., Fernández Ruiz M., Muttoni A.: Shear strength of R/C bridge cantilever slabs. In: Engineering Structures 30 (2008), pp. 3024-3033
- [2] Rombach G., Latte S.: Shear resistance of bridge decks without transverse reinforcement (in German). In: Beton- und Stahlbetonbau 104 (2009) No. 10, pp. 642-656
- [3] Reissen K., Hegger J.: Experimental investigations on the shear-bearing behavior of bridge deck cantilever slabs under wheel loads (in German). In: Beton- und Stahlbetonbau 108 (2013) No. 5, pp. 315-324
- [4] Lantsoght E., van der Veen C., Walraven J.: Shear in one-way slabs under concentrated load close to support. In: ACI Structural Journal 110 (2013) No. 2, pp. 275-284
- [5] Chang T.S., Kesler C.E.: Static and fatigue strength in shear of beams with tensile reinforcement. In: ACI Journal 29 (1958) No. 12, pp. 1033-1057
- [6] Schläfli M., Brühwiler E.: Fatigue of existing reinforced concrete bridge deck slabs. In: Engineering Structures 20 (1998) No. 11, pp. 991-998
- [7] *fib*: Model Code 2010 – Final draft, Volume 1 and 2. In: *fib* Bulletin 65 (2012) 350 p. & Bulletin 66 (2012) 370 p.
- [8] Muttoni A., Fernández Ruiz M.: Shear strength of members without transverse reinforcement as function of critical shear crack width. In: ACI Structural Journal 105 (2008) No. 2, pp. 163-172.